Human Factors and Operations Issues in GPS and WAAS Sensor Approvals: A Review and Comparison of FAA and RTCA Documents

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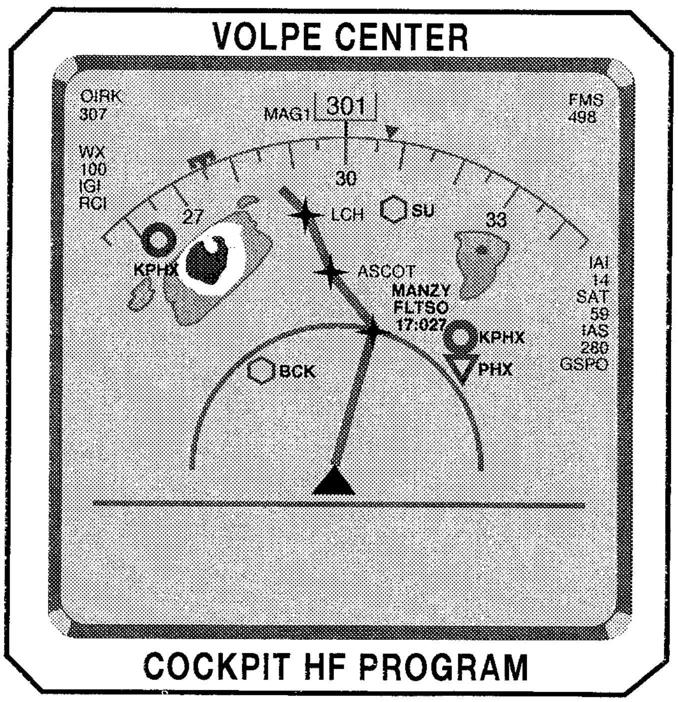

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This report is the culmination of the first task in a project to evaluate human factors and operations issues associated with the integration of Class C Global Positioning System (GPS) sensors and Class Beta GPS/Wide Area Augmentation System (WAAS) sensors into navigation systems in low-end transport category aircraft. The objective of the project is to provide aircraft certification specialists with information and, eventually, with a job aid to help them evaluate GPS and GPS/WAAS sensors within integrated navigation systems. The first task of the project was to compare the requirements of the various FAA and industry documents currently used in the approval of GPS and GPS/WAAS sensor equipment and installation. The impact of the use of Required Navigation Performance (RNP) standards on approval also was evaluated. The comparison of the requirements specified in the document is presented in table form and major differences are discussed.

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PREFACE

This report is the culmination of the first task in a project to assist aviation certification specialists in the evaluation of human factors and operations issues in the approval of Global Positioning System (GPS) Class C and GPS/Wide Area Augmentation System (WAAS) Class Beta equipment. This document was submitted by Monterey Technologies, Inc., under a contract with Battelle (Subcontract No. 87929 (477302)). Dr. Michael McCauley served as the program manager for Monterey Technologies, Inc. Mr. Donald Eldredge served as the program manager for Battelle. Mr. Tom Hazard of Monterey Technologies, Inc., reviewed and provided comments on the initial draft of this document. The contributions and support of Dr. McCauley, Mr. Eldredge, and Mr. Hazard are greatly appreciated by the author.

This report is part of a continuing effort at the John A. Volpe National Transportation Systems Center (Volpe Center) to assist the Federal Aviation Administration (FAA) aviation safety professionals in the understanding and application of human factors principles in GPS applications. Special thanks to Dr. Thomas McCloy (AAR-100) for monitoring this effort. Dr. Daniel Hannon and Ms. Colleen Donovan directed this project for the Volpe Center. The direction and support of Dr. Hannon and Ms. Donovan in this effort are greatly appreciated.

Several FAA aviation safety professionals, including aircraft certification specialists and the Northwest Mountain Region Aircraft Certification Office and members of the FAA Satellite Operations Implementation Team (SOIT), provided invaluable input to this effort. Special thanks are extended to Peter Skaves of the Northwest Mountain Region Aircraft Certification Office and Bruce DeCleene and Susan Cabler of AIR-130. Thanks also are extended to Rachel Daeschler, Catherine Gandolfi, and Rosanne Ryburn of the Northwest Mountain Region Aircraft Certification Office for their input on this project.

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ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (ha) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

$°C = 5/9(°F - 32)$

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

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$°F = 9/5(°C) + 32$

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CENTIMETERS	0	1	2	3	4	5	6	7	8	9	10	11	12	13

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

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EXECUTIVE SUMMARY

This report is the culmination of the first task in a project to evaluate human factors and operations issues associated with the integration of Class C Global Positioning System (GPS) sensors and Class Beta GPS/Wide Area Augmentation System (WAAS) sensors into navigation systems in low-end transport category aircraft. The objective of the project is to provide aircraft certification specialists with information that will help them in the evaluation of GPS and GPS/WAAS sensors within integrated navigation systems. The first task of the project was to compare the requirements of the various FAA and industry documents currently used in the approval of GPS and GPS/WAAS sensor equipment and installation. The impact of the use of required navigation performance (RNP) standards on approval also was evaluated.

This document describes both the GPS and GPS/WAAS navigation systems and equipment classifications. The major difference between GPS and GPS/WAAS systems is improved accuracy, integrity, continuity, and availability of GPS/WAAS systems (through the use of differential corrections) over GPS systems. Class C GPS sensors, together with an integrated navigation system, may be approved as supplemental means of navigation, while GPS/WAAS Class Beta sensors, when combined with an integrated navigation system, are expected (in the near future) to be approvable by the FAA as a primary means of navigation.

The GPS and GPS/WAAS equipment approval process is described. Five approval documents — 1) TSO-C129A, 2) RTCA DO-208, 3) RTCA DO-229, 4) AC 20-130A, and 5) RTCA 192-96 — and three supporting documents were reviewed. The review served two main purposes: 1) evaluation of the approval process and the identification of problems within the process and the documents, and 2) a detailed comparison of the requirements of the different documents for GPS and for GPS/WAAS sensors.

The evaluation of the documents and discussion with FAA personnel revealed potential areas for improvement of the approval documentation. Some of the documentation is difficult to understand and apply. Individuals at different Aircraft Certification Offices (ACOs) as well as manufacturers and operators may have different interpretations of the same information. At the time this document was prepared, not all of the FAA policy documentation regarding GPS/WAAS equipment was available. With GPS equipment, the documentation is difficult to use because it requires a great deal of cross referencing. Another problem is the distinction between technical standard order (TSO) authorization of equipment and approval of installations. TSOs are intended only to address equipment requirements, and cannot address installation requirements. TSO-C129 specifies requirements that apply to the multisensor system with which the equipment is to operate. This ensures that sensors provide an acceptable interface, but it also places a burden on the applicant who must use an FMS in order to demonstrate compliance. In many cases this situation is further complicated by the fact that the applicant is not the manufacturer of the FMS. In addition, some ACO engineers interpret the equipment interface requirements of TSO-C129 as installation requirements and are unsure how to approve equipment (in accordance with a TSO) independent of an installation.

The comparison of the requirements specified in the documents is presented in table form and major differences are discussed. The comparison revealed a high level of similarity between GPS and GPS/WAAS sensor requirements. While many requirements are the same, they are organized and worded differently, so the only way to identify common requirements is to carefully read each document. There were a number of differences between the GPS and GPS/WAAS requirements that did not appear to be specifically related to conceptual differences between the systems. Rather, many of the differences may be due to the increased availability of information at the time of the GPS/WAAS publication (1996) than at the time of the GPS publication (1991). One difference in requirements that was due to technological differences between the two systems was the treatment of accuracy and integrity requirements, including alerting and annunciation of accuracy or integrity problems.

The impact of required navigation performance for area navigation (RNP RNAV) on GPS and GPS/WAAS approvals also was considered. RNP RNAV is a concept intended to enable user-preferred trajectories and to promote free-flight by specifying minimum accuracy and integrity requirements for these operations. GPS and GPS/WAAS manufacturers may want to meet RNP RNAV requirements as well as GPS equipment requirements. A comparison of GPS and GPS/WAAS requirements with RNP RNAV requirements (as described in RTCA 192-96) revealed a few requirements unique to RNP RNAV approvals though GPS/WAAS requirements include requirements that are equivalent. Other than a requirement for parallel offsets and additional holding capabilities, equipment that meets the human factors and operations requirements of RTCA DO-229 for GPS/WAAS should meet the requirements of RNP equipment. Equipment approved to TSO-C129 rather than TSO-WAAS will have to be evaluated more carefully to ensure that all of the additional requirements of RTCA 192-96 have been met.

This review showed that the documentation and process for GPS and GPS/WAAS Class C sensor approvals is somewhat complicated. Generally, the documentation is thorough, but in some cases is difficult to interpret and difficult to cross-reference. There are efforts underway to account for some of the difficulties related to use of the documentation. First, TSO-C129 is being updated (TSO-C129B) to refer to the newer requirements of RTCA DO-229. Second, a checklist for approval of GPS/WAAS equipment is under development.

1. INTRODUCTION

Navigation using the Global Positioning System (GPS) is becoming more common in the aviation community. Advancements to GPS including the Wide Area Augmentation Systems (WAAS) will make the use of GPS even more attractive to airlines and pilots; it potentially will allow the use of GPS/WAAS as the primary means of navigation. Manufacturers of new aircraft are incorporating GPS navigation sensors into their flight management systems. Owners of existing aircraft are either installing stand-alone GPS systems or are incorporating GPS sensors into integrated navigation or flight management systems. A similar trend is expected in the future for GPS/WAAS equipment. The Federal Aviation Administration (FAA) is tasked with the problem of satisfying the demands of airlines and pilots to update their aircraft while maintaining a level of safety over the various types of GPS equipment and GPS installations.

The goal of this project is to evaluate the human factors and operations issues associated with the integration of Class C GPS sensors and Class Beta GPS/WAAS sensors into navigation systems in low-end transport category aircraft. Low-end transport category aircraft typically refers to older aircraft flown in part 121 or part 135 operations that do not have "glass cockpits" and were manufactured prior to the development of GPS. FAA Aircraft Certification Offices (ACOs) are responsible for technical standard order (TSO) authorization of GPS and GPS/WAAS equipment and for the first-time approval of GPS and GPS/WAAS installations. The approval of GPS or GPS/WAAS sensor installations in low-end transport aircraft is different from the approval of both stand-alone GPS systems (GPS Class A or GPS/WAAS Class Gamma) and GPS sensors in flight management systems of newer glass cockpit aircraft (GPS Class C or GPS/WAAS Class Beta). With stand-alone equipment, the equipment TSO authorization requirements cover all aspects of the equipment, including both human factors and operations issues. The navigation sensor and user interface are contained in the same unit and can be evaluated independently from the installation (although each installation must also be approved for airworthiness). With the newer glass cockpit aircraft, the GPS sensor equipment may be evaluated through a TSO authorization. Then the installation is either evaluated as a part of a flight management system in the original type certificate of an aircraft or the sensor is easily integrated into a flight management system that has already been evaluated for human factors and operations and requires little, if any, changes to the user interface.

In incorporating sensors into navigation systems in low-end transport category aircraft, performance of the GPS and GPS/WAAS sensor equipment may receive TSO approval, but evaluation of the user interface of the integrated system is not specified (though it is implied) in the equipment approval documentation and may be more complicated than the evaluation of stand-alone or glass cockpit systems. The incorporation of GPS or GPS/WAAS sensors may constitute a major change in the avionics on the flight deck. Careful consideration must be given to human factors and operations issues for each installation, since each installation is likely to be unique.

Another issue related to the installation of GPS and GPS/WAAS sensors is the accuracy of the equipment. GPS systems indicate accuracy using horizontal integrity level (HIL) and GPS/WAAS systems indicate accuracy using horizontal protection level (HPL) for GPS/WAAS systems. Another way of indicating accuracy is through estimated position uncertainty (EPU) and required navigation performance (RNP). In the future, aircraft that demonstrate navigation accuracy better than certain RNP values may be permitted to fly special procedures or airspace associated with various RNP criteria. Many of the human factors and operations requirements to meet RNP criteria are the same as those for GPS and GPS/WAAS. However, there are a few differences or additional criteria described in chapter 6 that will affect installation requirements for GPS and GPS/WAAS equipment.

Documentation is available that describes equipment approval requirements and airworthiness approval requirements for GPS sensors and associated navigation or flight management systems. Documentation also is available for approval of GPS/WAAS equipment, though the acceptance of this documentation by the FAA (through a TSO) is in draft form. Draft documentation is available describing RNP criteria. The first task of this project was to review and compare the documentation available on equipment approval, installation approval, and RNP criteria to identify human factors and operations issues associated with the installation of GPS and GPS/WAAS equipment. This paper describes the results of the document review.

There are seven main sections in this document. These include:

Chapter 2 System description of both GPS and GPS/WAAS.

Chapter 3 Approval process for GPS and GPS/WAAS equipment.

Chapter 4 GPS and GPS/WAAS equipment classifications.

Chapter 5 Description of required navigation performance (RNP).

Chapter 6 Summary of each of five approval documents — 1) TSO-C129A, 2) RTCA DO-208, 3) RTCA DO-229, 4) AC 20-130A, and 5) RTCA 192-96.

Chapter 7 Comparison of the approval requirements from the five documents presented in table form and a discussion of the major differences between human factors and operations issues in GPS and GPS/WAAS, as well as the impact of RNP criteria on these installations.

Chapter 8 Recommendations for further work to assist ACOs in the approval of GPS and GPS/WAAS sensor installations in low-end transport category aircraft.

2. SYSTEM DESCRIPTION

This section describes both GPS and the GPS/WAAS. Sources for the information in this section include Adler and Ruelos (1993), Department of Transportation (DOT) and Department of Defense (1993), Joint DOD/DOT Task Force on GPS (1993), RTCA, Inc. (1996), and DeCleene (1996).

2.1 Global Positioning System

The Navstar GPS is a satellite-based radionavigation system jointly managed by the Department of Defense (DOD) and the DOT. GPS was originally developed as a military system. It is subject to limitations imposed by the DOD for national security reasons. However, the DOD and the DOT have undertaken a cooperative effort to make GPS available for use as an integral part of the civil radionavigation system.

GPS consists of three functional segments: space, control, and user. The space segment is a constellation of 24 satellites. The satellites orbit the earth at an altitude of about 10,900 nautical miles with four satellites in each of six different orbital planes. This constellation guarantees that at least four satellites will be greater than 5 degrees above the horizon with respect to the user anywhere in the world, at any time.

The control segment controls satellite operations. A master control station (MCS) is located at Falcon Air Force Base in Colorado. A worldwide network of five signal monitoring stations and three uplink ground antennas complete the control segment. Monitor stations collect and send GPS navigation signal data to the MCS for evaluation and determination of required corrections. Corrections to satellite atomic clocks or orbital parameters are relayed to the satellites from the ground antennas. Other satellite subsystems including power, thermal balance, and attitude are also monitored by the MCS.

The user segment is the GPS receiver that receives data from the satellite to compute position. GPS compares the time it takes to receive radio signals from each satellite to compute position. Data from four satellites are needed to solve an equation with four unknowns — latitude, longitude, altitude, and time. The time computation is required due to receiver clock error.

Accuracy and integrity are important GPS performance characteristics. Accuracy refers to the degree of conformity of a GPS position estimate to the true position. The service provided to civil users is called the Standard Position Service (SPS). The DOD employs a process called selective availability to degrade the accuracy of the GPS signal for SPS, the U.S. guarantees an SPS horizontal accuracy of 100 meters 95 percent of the time and 300 meters 99.99 percent of the time. Altitude (above WGS-84 ellipsoid) can be determined to within 140 meters 95 percent of the time.

GPS accuracy is much greater than any other en route navigation system. However, GPS accuracy is not sufficient for precision approach and departure (and would not be even if

selective availability was turned off). The type of augmentation to GPS known as differential GPS can provide lateral and vertical accuracy of around 5 to 10 meters and may be developed to allow for precision approach and departure. Currently, the Coast Guard operates a differential GPS system for maritime use. WAAS is one type of system that provides differential GPS corrections, yielding the accuracy, integrity, continuity, and availability for en route navigation through precision approach operation.

Integrity refers to the ability of the system to provide timely warnings to users when GPS data should not be used. Users must remain aware of the integrity of the GPS data. Since four satellites are required for GPS navigation, users must know if they are not receiving four satellites or if a satellite is not operating within tolerance.

There are several ways a user can monitor the integrity of the GPS data. One method is known as receiver autonomous integrity monitoring (RAIM). Using RAIM, the receiver monitors its own integrity and alerts the user if integrity is lost. However, RAIM requires five operational satellites with good geometry and is not always available. A second method is automatic monitoring through the use of other navigation sources or perhaps through the use of differential ground stations such as those provided by WAAS. For IFR use, the FAA currently requires automatic integrity monitoring — either RAIM or RAIM equivalent (through the use of other navigation sources or differential techniques such as WAAS).

Because of the potential for loss of integrity with the GPS system, the FAA does not allow operators to use GPS as the primary means of navigation except in certain circumstances (oceanic and remote areas). An alternate navigation system approved for the route to be flown must be installed and operational on the aircraft. In the airspace where GPS may be used as the primary means of navigation, the FAA requires that operators use a ground prediction program that predicts the availability of satellites over the proposed route at the proposed time, excludes any satellites that are unusable, and predicts whether navigation integrity and continuity can be maintained throughout the flight.

2.2 DGPS Wide Area Augmentation System

Differential techniques may be applied to GPS to achieve substantial improvements in position accuracy and to provide integrity information. Differential GPS (DGPS) uses information obtained from a land-based receiver at a surveyed site to determine and transmit corrections to users. DGPS systems have three basic components: 1) a land-based receiver that monitors and collects satellite data and compares the data with known survey position data, 2) a method of transmitting corrections determined at the site (or at a central control station) to users, and 3) user equipment that has hardware and software necessary to receive and apply the corrections to information received from GPS satellites.

There are several methods of transmitting DGPS data to users. Data can be transmitted over a small geographic area or over a broad geographic area. DGPS systems that transmit data over a fairly small area are known as local area augmentation systems (LAAS). LAAS data will

be transmitted from a ground-based site (such as an airport). DGPS systems that transmit over a broad area are referred to as wide area augmentation systems (WAAS). WAAS broadcasts will be transmitted via satellite to cover an area that is nearly hemispheric. The accuracy of DGPS systems is dependent on a number of factors, including the distance from the user to the reference site.

A WAAS is being developed for use in the U.S. National Airspace System (NAS). This WAAS uses ground stations to calculate GPS integrity and correction data and then uses geostationary satellites to broadcast GPS integrity and correction data to GPS/WAAS receivers. The WAAS is made up of an integrity and reference monitoring network, processing facilities, geostationary satellites, and control facilities. Reference stations and integrity monitors are data collection sites dispersed throughout the U.S. that use GPS/WAAS ranging receivers to collect data from the GPS and from the WAAS satellites. The reference stations forward the data to central data processing sites that determine differential corrections, ionospheric delay information, GPS/WAAS accuracy, and error bounds for monitored satellites. The central processing sites also generate navigation messages for the geostationary satellites and WAAS messages. The information from the central data sites are broadcast to users from the geostationary satellites.

The operational goal of WAAS is to augment the integrity and accuracy of GPS so that GPS/WAAS can replace the existing radionavigation infrastructure in the U.S. NAS. WAAS augments GPS to obtain the required accuracy for precision approaches and provides integrity, continuity, and availability of service that is not available with GPS without augmentation.

3. APPROVAL OF GPS AND GPS/WAAS SENSOR EQUIPMENT AND INSTALLATION

The process for obtaining approval to install and use GPS or GPS/WAAS equipment in low-end transport category aircraft is relatively complicated. The Code of Federal Regulations (CFRs) are the only regulatory documents that the equipment and installation must meet, but consistent with that code, operators must obtain airworthiness approval from the FAA in order to install and operate GPS or GPS/WAAS equipment. A process has been developed to provide manufacturers and operators with information needed to help obtain airworthiness approval. This process involves the use of voluntary guidelines in different forms. The guidelines are stated so that they provide a means, but not the only means, for obtaining airworthiness approval. This system allows the FAA and industry to publish standards for equipment that, even though they are voluntary, are usually followed because they shorten the time and ease the workload required for approval. Manufacturers or operators are permitted to choose alternate methods rather than meet the published standards to verify airworthiness. However, this is likely to entail more effort and take more time to receive FAA approval than is required if the published standards are followed.

The first voluntary step for GPS or GPS/WAAS equipment is authorization of the equipment in accordance with a TSO. With GPS equipment, TSO-C129 provides the minimum operational performance standards required for a GPS system or sensor to be identified with a TSO-C129 Class marking. This equipment authorization provides potential buyers of GPS equipment with the knowledge that the equipment has been designed and manufactured in accordance with the industry standard. In addition, buyers may find that FAA airworthiness approval of equipment (for supplemental navigation) with TSO-C129 authorization proceeds more smoothly and quickly than approval of equipment without TSO authorization. TSOs generally do not contain the actual guidelines for developing and testing the equipment. Rather, they reference industry and FAA developed standards such as RTCA Minimum Operational Performance Standards (MOPS), RTCA software development procedures, and RTCA environmental testing procedures. With GPS these documents include RTCA DO-208, DO-178B, and DO-160C. Where the FAA has identified exceptions to the industry standard (e.g., RTCA) documents, the TSO standard lists these exceptions. This is the case with TSO-C129 for GPS equipment.

Currently, there is no published TSO for the approval of GPS/WAAS equipment. However, the TSO is in draft form and an RTCA document (DO-229) with MOPS for GPS/WAAS has been published. The draft TSO (TSO-WAAS) references RTCA DO-229. It is expected that TSO-WAAS will establish a standard for GPS/WAAS equipment to be approved for primary means navigation.

After the manufacturer has obtained TSO authorization, the installation approval process begins. The FAA (usually the ACO) may allow installation of equipment that does not meet the TSO or meets the TSO with deviations. In this situation, the manufacturer or operator is required to show that the equipment meets the equivalent of the requirements called out in the TSO. The next step in the approval process is airworthiness approval of the equipment and installation by the FAA. A means of obtaining airworthiness approval may be described in an FAA document such as an advisory circular (AC). While there are no ACs specific to GPS or GPS/WAAS

sensors (AC 20-138 is specific to GPS equipment but it applies only to stand-alone equipment, not to Class C GPS sensors), there is an AC (AC 20-130A) that describes guidelines for obtaining airworthiness approval of navigation or flight management systems integrating multiple navigation sensors. This document applies to GPS sensors but not to GPS/WAAS sensors. The AC calls out performance requirements, testing (bench tests, ground tests, and flight tests) requirements, and data evaluation requirements. The airworthiness approval may be completed by different FAA offices depending on the complexity of the equipment and installation. With first time approvals of GPS equipment intended for IFR use, an ACO is required to perform the airworthiness approval.

For both the equipment approval and the installation airworthiness approval, manufacturers and operators will be required to provide the FAA with data showing that they have met the performance standards called out in the various documents. This data will include information such as wiring diagrams and environmental test results. The FAA may also choose to inspect and test the equipment according to the procedures called out in the standards.

Unfortunately the standards used in the approval process for GPS equipment are subject to different interpretations. Some of the documentation is written in a manner that makes it difficult to understand and apply. Individuals at different ACOs as well as manufacturers and operators may interpret the information differently. With GPS/WAAS equipment, all of the needed information is not yet available. In addition, there are slight differences in the requirements in the various standards. There are also differences in the requirements for GPS equipment and GPS/WAAS equipment. Another problem is the distinction between TSO approval of equipment and approval of installation. While TSOs do not include installation requirements, they may (as in the case of TSO-C129) contain requirements that the manufacturer show that the equipment interface properly with installed equipment such as an FMS. ACO engineers are then unsure how to approve equipment independent of the installation. A GPS sensor authorized to TSO-C129 on one aircraft may not meet the same standards when installed on another aircraft. These TSO requirements to ensure installed equipment performance also are slightly different than the requirements listed in ACs intended to include installation requirements. It is the goal of this project to compare the requirements of the various documents for GPS sensor installations.

Another level of approval that manufacturers may desire is approval of equipment to specific RNP criteria. The RNP concept, benefits of approval, and approval requirements are described in chapter 5.

4. GPS AND GPS/WAAS TSO EQUIPMENT CLASSIFICATION

The FAA has created a classification of different types GPS and GPS/WAAS equipment. The classification consists of a functional class and an operational class. For example, a GPS receiver in functional Class A and operational Class 1 is referred to as a Class A(1) receiver. TSO-C129 describes the classes for GPS approval. RTCA DO-229 describes the classification for GPS/WAAS equipment. TSO-WAAS (draft) adopts the classification specified in RTCA DO-229 except that it does not yet recognize operational Classes 3 and 4 (that allow the use of GPS/WAAS for precision approach). Table 1 displays the different functional and operational classes for GPS and table 2 displays the functional and operational classes for GPS/WAAS equipment.

Table 1. GPS TSO-C129 Equipment Classification

TSO-C129 Classification of GPS Equipment	
Functional Class	
A	GPS sensor data and navigation capability (stand-alone receiver).
B	GPS sensor data to an integrated navigation system (i.e., FMS, multisensor, navigation system, etc.).
C	GPS sensor data to integrated navigation system (as in Class B) which provide enhanced guidance to an autopilot, or flight director, to reduce flight technical errors.
Operational Class	
1	Uses RAIM for integrity monitoring and approved for use in oceanic, en route, terminal, and nonprecision approach operations.
2	Uses RAIM for integrity monitoring and approved for use in oceanic, en route, and terminal operations.
3	Uses an integrated navigation system that provides integrity equivalent to RAIM and approved for use in oceanic, en route, terminal, and nonprecision approach (not applicable to Class A equipment).
4	Uses an integrated navigation system that provides integrity equivalent to RAIM and approved for use in oceanic, en route, and terminal operations (not applicable to Class A equipment).

Table 2. GPS/WAAS RTCA DO-229 Equipment Classification

RTCA DO-229 Classification of GPS/WAAS Equipment	
Functional Class	
Beta	GPS/WAAS sensor data to an integrated navigation system. Provides integrity in the absence of WAAS using FDE.
Gamma	GPS/WAAS sensor and a navigation function to provide path deviations relative to a selected path (stand-alone). Provides integrity in the absence of WAAS using FDE. Includes database, display outputs, and pilot controls.
Delta	GPS/WAAS sensor and a navigation function to provide path deviations relative to a selected path. Does not provide a database or direct pilot controls. Applicable only to Class 4 for precision approach, providing an ILS replacement.
Operational Class	
1	Supports oceanic and domestic en route and terminal operation. Must check WAAS-reported integrity status of GPS satellites, but not required to apply differential corrections.
2	Supports oceanic and domestic en route, terminal, nonprecision approach, and departure operation. In nonprecision approach mode, must apply long-term and fast WAAS differential corrections.
3	Supports oceanic and domestic en route, terminal, nonprecision approach, precision approach, and departure operation. In precision approach mode, must apply long-term, fast, and ionospheric corrections.
4	Supports precision approach operation. Intended as replacement to ILS, applicable only to Class Delta. (Delta-4 equipment is likely to also meet requirements for Beta-1,-2, or -3).

5. REQUIRED NAVIGATION PERFORMANCE

Required navigation performance (RNP) is another important concept in the approval of GPS and GPS/WAAS equipment. RNP was defined by ICAO (Doc. 9650) as a statement of navigation performance accuracy, integrity, continuity, and availability necessary for operations within a defined airspace. RTCA in RTCA 192-96, draft, has modified this concept slightly in its definition of RNP RNAV: "A statement of the navigation performance accuracy necessary for operation within a defined airspace. Note that there are additional requirements, beyond accuracy, applied to a particular RNP type." The RNP RNAV minimum aviation system performance standard (MASPS) (RTCA 192-96, draft) defines the additional requirements beyond accuracy.

Accuracy, integrity, continuity, and availability are currently included in GPS and GPS/WAAS approvals through requirements that differ slightly from those described for RNP RNAV approvals in RTCA 192-96. For example, TSO-C129 lists required position fixing error, CDI centering, flight technical error (FTE), and requirements for RAIM or other types of integrity monitoring. The concept of RNP (and RNP RNAV) was developed as a means of describing navigation requirements without identifying a specific sensor or navigation technology.

A draft of MASPS standards for RNP for area navigation (RNAV) (RTCA 192-96) has been written specifying performance standards for area navigation equipment to meet in order to operate in RNP RNAV designated airspace or using RNP RNAV designated procedures. It is believed that equipment meeting RNP criteria will allow users to benefit from approvals to operate in desirable airspace or using desirable procedures. RNP RNAV criteria are specified using RNP RNAV types that indicate the accuracy and integrity of the equipment. Better equipment accuracy and integrity will allow equipment to meet more stringent criteria (e.g., RNP-1 RNAV for 1 nautical mile versus RNP-4 RNAV for 4 nautical miles) and operate using more RNP routes and procedures. While the FAA has not yet adopted the RNP RNAV standards, manufacturers may want to develop GPS/WAAS equipment that meet the standards specified in RTCA 192-96 to ensure accuracy and integrity that will allow purchasers to take advantage of future RNP routes and procedures. Because manufacturers obtaining approvals of GPS and GPS/WAAS sensors may also want approvals of their equipment to various RNP RNAV types, this document has reviewed human factors and operations issues associated with RNP RNAV requirements (as described in RTCA 192-96) as they compare to the requirements of GPS and GPS/WAAS equipment requirements.

6. GPS, GPS/WAAS, AND RNAV EQUIPMENT AND INSTALLATION APPROVAL DOCUMENTS

The existing requirements for GPS and GPS/WAAS equipment and installation approval were reviewed in order to identify and compare human factors and operations issues. Five requirements documents and three supporting documents were reviewed. A summary of each of the five requirements documents and a description of the three supporting documents follows.

6.1 RTCA DO-208 - Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS) (RTCA, 1991)

RTCA DO-208 is a combined industry and government document that contains minimum operational performance standards for airborne supplemental navigation equipment (2D and 3D) using GPS. It contains most of the requirements for approval of GPS equipment for IFR use called out by TSO-C129. The requirements cover equipment performance including user interface issues. Though the document discusses integrated and multisensor systems, the document does not specify different requirements for Class C (sensor only) equipment versus Class A (stand-alone systems) equipment.

6.2 TSO-C129A - Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS) (FAA, 1992)

TSO C129A prescribes the minimum performance standard that "supplemental" area navigation equipment using GPS must meet to be identified as TSO-C129A approved. In general, TSO-C129A references the minimum performance standards of Section 2 of RTCA DO-208 as requirements for approval of GPS equipment. TSO-C129A defines the different equipment classes (as described previously) and lists exceptions to the RTCA DO-208 document for each of the equipment classes. Since this project deals specifically with GPS sensor (Class C(1) and C(3)) equipment, the section describing exceptions to RTCA DO-208 for Class C() equipment was reviewed for integration with the RTCA DO-208 requirements to identify the complete list of requirements for GPS Class C(1) and C(3) equipment.

While RTCA DO-208 does not make a distinction in requirements for Class C equipment, TSO-C129A does. TSO-C129A exempts Class C equipment from some requirements. Generally, requirements dealing specifically with user interface issues such as data entry and information display are exempted by TSO-C129A, presumably because Class C equipment are sensors only and do not include user interface components. However, TSO-C129A does state that the integrated navigation systems that use Class C sensors may have to meet the requirements listed. That is, TSO-C129A exempts Class C equipment from many of the user interface requirements while at the same time implying that the equivalent of the requirements must be met when integrating the sensors with other equipment. Unfortunately, the actual installation requirements

and the factors that determine the user interface requirements of integrated navigation systems are not specifically stated.

One example of this problem is the statement in TSO-C129A that the requirements of RTCA DO-208 paragraph 2.2.1.13 (Integrity alarm for GPS receivers) do not apply to Class C3 and Class C4 equipment. While Class C3 and C4 equipment is not required to use RAIM for integrity monitoring, an equivalent method must be used. The statement in paragraph 2.2.1.13.1 — *"Regardless of the method used to ensure integrity, the integrity system shall meet the general specifications given in Table 2-1"* should probably apply to all systems, regardless of the method of ensuring integrity. The annunciation of integrity alarm (2.2.1.13.2) is also important regardless of the method of ensuring integrity, however, TSO-C129A exempts GPS Class C3 and C4 equipment from these requirements.

Another example of a difficulty involved in interpreting TSO-C129A is the reference to equivalence of requirements in the section "Exceptions to RTCA DO-208 for Class A( ) equipment" for Class C equipment. When the reader turns to the referenced section, the wording often lists requirements specific to Class A1 equipment. It is assumed that Class C1 equipment must meet the equivalent of the requirement for Class A1 equipment and that Class C2 must meet the equivalents of Class A2, etc.; however, this is not clearly stated in the document. In addition, this reference adds an additional translation of information (page turning and cross-referencing within TSO-C129A and between TSO-C129A and RTCA DO-208).

6.3 RTCA DO-229 - Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment (RTCA, 1996)

RTCA DO-229 is a combined industry and government document that provides minimum operational performance standards for GPS/WAAS. It is similar to the RTCA DO-208 document except that it applies to GPS/WAAS equipment rather than GPS equipment. The draft FAA Order TSO-WAAS references RTCA DO-229 as an acceptable means for approval of GPS/WAAS equipment as TSO-C129A does for GPS equipment. TSO-WAAS states that the standards in RTCA DO-229 should be used as the standards for approval of GPS/WAAS equipment.

RTCA DO-229 does make a distinction in requirements for Class Beta( ), Gamma( ), and Delta(4) equipment. The requirements for Class Beta( ) equipment generally deal with accuracy and functionality and do not include user interface requirements. The document does, however, state the following:

> *"There are a number of integration issues associated with the installation of Class Beta equipment (such as compatibility with the navigation computer). Compatibility will have to be established for each navigation computer; the appropriate standards for determining that compatibility are not included in this standard . . . Class Beta equipment, together with the navigation computer, database, controls, and display will provide equivalent performance to Class Gamma and Delta equipment"*

Therefore, while RTCA DO-229 does not provide requirements for the human factors and operations issues associated with the integrated navigation system user interface for GPS/WAAS Class Beta equipment, it does suggest that the installed sensor and integrated navigation system should meet the same criteria as listed for Class Gamma and Delta equipment. As with GPS equipment, the document does not specifically list requirements or factors influencing the evaluation of user interface of GPS/WAAS Class Beta sensors in integrated navigation systems. It does imply, however, the human factors and operations requirements in section 2.2 for Class Gamma equipment should be applicable to integrated navigation system using Class Beta sensors.

A few other sections of RTCA DO-229 should also be helpful in evaluating Class Beta integrated navigation systems. Section 2.5 covers test methods and procedures, and section 2.5.10.2 provides procedures for human factors bench tests. The human factors bench tests cover equipment usability, display brightness and readability, audible alarms, and controls.

6.4 AC 20-130A - Airworthiness Approval of Navigation or Flight Management Systems Integrating Multiple Navigation Sensors (FAA, 1996)

AC 20-130A establishes an acceptable means of obtaining airworthiness approval of multisensor navigation of flight management system integrating data from multiple navigation sources for use as a navigation system. Since RTCA DO-208 and RTCA DO-229 deal with approval of the GPS or GPS/WAAS equipment only, the documents do not require evaluation of the installation and integration (though they do list installed equipment requirements). AC 20-130A provides installation and integration requirements for navigation and flight management systems integrating multiple navigation sensors including GPS, Omega/VLF, Loran-C, VOR/DME, Multiple DME, or INS/IRU sensors. AC 20-130A states that it does not apply to systems incorporating GPS/WAAS sensors.

AC 20-130A lists requirements for GPS Class C equipment including a requirement that the GPS sensor be approved in accordance with an applicable TSO (e.g., TSO-C129A) and requirements dealing with human factors and operations aspects of the user interface. This document describes a method for obtaining airworthiness approval of a GPS sensor in an integrated navigation or flight management system. It provides a list of airworthiness criteria for first time and follow-on IFR or VFR approval. Since this project deals specifically with ACO approval of Class C GPS equipment in low-end transport category aircraft, the section on first time IFR approvals was reviewed. Both the airworthiness requirements and the approval process evaluations (bench test, data evaluation, ground test, and flight test) were reviewed. AC 20-130A covers human factors, operations, accuracy, and reliability of the installed equipment.

6.5 RTCA Paper No. 192-96/SC 181-061 Minimum Aviation Performance System Standards: Required Navigation Performance for Area Navigation Draft 8 (RTCA, 1996)

The final requirements document reviewed was RTCA 192-96. RTCA 192-96 is a draft MASPS for area navigation systems operating in an RNP RNAV environment. Of interest is whether approvals of multisensor systems which incorporate GPS Class C or GPS/WAAS Class Beta

equipment to be used in RNP RNAV environments will have additional or differing human factors and operations issues than approvals that do not include use of GPS or GPS/WAAS in RNP environments. RTCA 192-96 describes RNP and related concepts and defines RNP RNAV and RNP-x RNAV types. Information is provided on user interface requirements including human factors issues and operational capabilities. Appendix E of RTCA 192-96 describes RNP RNAV assessment criteria for existing aircraft. This section is useful in the application of GPS sensors into integrated navigation systems of low-end transport category aircraft. Appendix E lists additional requirements for existing systems to meet the MASPS for RNP RNAV.

6.6 Supporting Documents

Three supporting documents were reviewed:

1) "FAA Human Factors and Operations Checklist for Stand-Alone GPS Receivers (TSO-C129A1)" (Huntley, et al., 1995),
2) "A Review of Principles and Guidelines for the Design of Controls and Displays for Stand-Alone GPS and Loran Receivers" (McAnulty, 1994), and
3) *Global Positioning System, A Guide for the Approval of GPS Receiver Installation and Operation* (Wright, 1996).

The "Human Factors and Operations Checklist for Stand-Alone GPS Receivers" provides a human factors and operations evaluation tool for stand-alone GPS receivers. It includes both a bench test and a flight test. This document includes the requirements of TSO-C129, RTCA DO-208, and AC 20-138 (the stand-alone GPS receiver equivalent of AC 20-130A). It also includes human factors guidelines from other FAA, military, and industry documents. This document uses an evaluation (rather than a guideline) approach, providing evaluators with scenarios to follow and evaluation considerations for each scenario. While it is not a required document for approval, it is a valuable tool for ensuring that GPS stand-alone equipment meets <u>at least</u> the human factors requirements of TSO-C129 and AC 20-138. Many of the same procedures and requirements should be applicable to an integrated navigation system with a GPS sensor installation.

McAnulty (1994) discusses some aspects of automation and GPS and describes GPS interfaces. This document lists the relevant human factors guidance from RTCA DO- 208 and discusses the literature available for design guidance. It provides more of a design (rather than evaluation) guideline approach to the design of controls and displays. It includes detailed information about the selection, design, and arrangement of controls and displays.

The GPS installation and approval guide (Wright, 1996) lists the requirements of flight standard district office aviation safety inspectors for approving GPS installation and operation. This document provides checklists for the various phases of this approval process. Items in the checklist include guidance on all the aspects of the approval process, not just human factors and operations issues. This document covers field airworthiness approvals only; therefore, it may not consider all the issues that are involved in a first-time approval. As is the case with the human factors and operations checklist, the guide is not a required document, but it provides a valuable

tool for aviation safety inspectors to ensure that a new system meets all of the various installation and operation requirements documents.

7. HUMAN FACTORS AND OPERATIONS ISSUES, SIMILARITIES AND DIFFERENCES WITH GPS VERSUS GPS/WAAS EQUIPMENT

7.1 Comparison Tables of Human Factors, Operations, and Accuracy Issues for GPS and GPS/WAAS Requirements Documents

Table 3 lists the requirements for GPS and GPS/WAAS called out by the documents reviewed. The number and the title of the guideline is presented in the table. If the intent of the requirement was similar across the different documents, they are written in the same row. Also, the requirements were grouped into three separate areas: 1) traditional human factors requirements, 2) user interface functional characteristics, and 3) system integrity, annunciations, alerts, and accuracy. Within these groups, an attempt was made to organize the items so that related issues are close together. Therefore, differences between the documents can be seen by noting the blank areas (or holes) in the tables.

Only requirements determined to be directly related to human factors issues, operational issues (i.e., the functions of the equipment that are apparent to the pilot — functions that may be selected, output that may be viewed), or accuracy issues, are included. Examples of requirements that are not covered include maintenance requirements, fire resistance, signal processing characteristics, equipment performance in environmental conditions, and automatic satellite selection. Requirements that were questionable as to whether they should be considered human factors or operations issues (e.g., display update rate, lateral maneuver anticipation) were included.

The table is organized with the three documents that apply to GPS (TSO-C129, RTCA DO-208, and AC 20-130A) on the left, then the document that applies to GPS/WAAS (RTCA DO-229), and finally the document that applies to RNAV approvals (RTCA 192-96) on the right. There currently is no GPS/WAAS document that deals specifically with installation airworthiness approval.

Column one lists the combined requirements of RTCA DO-208 and TSO-C129A. This column lists requirements called out in RTCA DO-208 with cells coded to indicate TSO-C129A exceptions to the requirements. Cells that are grayed are items that TSO-C129A states do not apply to Class C equipment. Cells that have an asterisk (*) are items that TSO-C129A states a change to the existing requirement in RTCA DO-208 or states that an equivalent capability must be provided by the Class C equipment. There are some requirements that one paragraph of TSO-C129 stated Class C equipment was exempt from (shaded) and a different paragraph of TSO-C129 stated a change to or equivalent capability requirement (*) for Class C equipment. It is assumed that these items (with shading and an asterisk) should be considered requirements.

Column two lists the requirements of RTCA DO-208 that are not specifically sensor equipment requirements but should be met by the integrated navigation system once the equipment is installed.

Column three lists the requirements of AC 20-130A for GPS sensors used under IFR, first time installation approval. In the cases where a requirement is described twice in the document (for example, some requirements are described as an airworthiness requirement, a bench test item, and a flight test item), only the first mention of the item in the document is noted.

Column four lists RTCA DO-229 requirements from section 2.1 that include requirements applicable to Beta, Gamma, and Delta equipment for en route, terminal, nonprecision approach, and precision approach modes and the requirements called out in sections 3.1 and 3.2 covering installed equipment performance for Class Beta equipment. In the case where a requirement of the same title is slightly different for different operations, the numbers for each listing are noted, then the title of the requirement.

Column five covers requirements called out in RTCA DO-229 that are not listed as requirements of Class Beta sensors, however, the document states that the integrated navigation equipment should meet the equivalent of these requirements. They include requirements from sections 2.2 that are applicable to Gamma equipment for en route, terminal, nonprecision approach, and precision approach modes and requirements from section 3.3 covering installed equipment performance for Class Gamma equipment for all operating modes. Where a section lists several related requirements, only the number of the main heading or first requirement is listed. This column also includes vertical navigation (VNAV) requirements from Appendix F of RTCA DO-229 which are subject to change since RTCA Special Committee 181 is developing VNAV criteria in support of evolving RNP concepts.

Column six covers requirements described in the MASPS for RNP RNAV (RTCA 192-96). These include both original equipment requirements and existing equipment requirements as described in Appendix E of RTCA 192-96.

Table 4 presents the same information in summary form (without exact titles, section numbers, or the reference to be implied for actual requirements) so that it is easy to see which of the documents cover various aspects of the system or installation. The differences between GPS and GPS/WAAS requirements are also easily noted in table 4.

Table 3. Human Factors, Operations, Accuracy Requirements/Issues

GPS Class C			GPS/WAAS Class Beta		RNP RNAV
Required of sensor by TSO-C129 A and/or RTCA DO-208 Shaded = exempt by TSO * = changed by TSO	Required (implied) of integrated navigation system by RTCA DO-208 (installed equipment performance)	Requirement of integrated navigation system by AC 20-130A	Required of sensor by RTCA DO 229 (including installed equipment requirements)	Required (implied) of integrated navigation system by RTCA DO 229 (Class Gamma equivalent)	Required by RTCA 192-96 for operation in RNP RNAV airspace (there may be some differences in requirements depending on the level of RNP RNAV airspace desired)
Traditional Human Factors Requirements					
2.1.4 Operation of controls* 2.1.5 Accessibility of controls*	3.1.1.1 Accessibility	9b(8) System controls	3.1.1.1 Accessibility	2.2.1.1.1 Controls 2.2.1.1.1.1 Operation 3.3.1.1.3 Operation of controls 3.3.1.3.2.5 Controls accessibility, usability, visibility 3.3.1.1.4 Accessibility of controls	3.4.2 Displays and controls
				3.3.1.1.5 Arrangement of controls	1.2.4.1 Controls, displays, and system alerting
2.1.8 Control/display readability		9b(8) System controls (readable)		2.2.1.1.1.2 Control labels	
	3.1.4 Inadvertent turnoff	9b(8) System controls	3.1.1.3 Inadvertent turnoff		3.4.2 Displays and controls
2.1.7 Control/display capability				3.3.1.1.2 Control/display capability	
2.1.8 Control/display readability	3.1.2 Display visibility	9b(3) Location of system displays		2.2.1.1.3.1 Brightness, contrast, and color 2.2.1.1.3.2 Angle of regard 3.3.1.1.1/3.3.3.1.1/ 3.3.4.1.1 Display visibility	3.4.2 Displays and controls
		9c(1)(ii)(B) Cockpit layout		3.3.1.3.1.1 Cockpit layout of installed equipment	
				3.3.1.2.2 Data entry capability	
				2.2.1.1.2/ 3.3.3.3.2.1 Equipment operating procedures (time critical functions)	
		9c(1)(iv)(J) Crew workload		3.3.1.3.2.6 Crew workload	1.2.4.1 Controls, displays, and system alerting 3.4.1 General
				2.2.1.1.3.3 Symbology	
				2.2.1.1.3.4 Alphanumerics	
				2.2.1.1.5 Set of standard abbreviations	
				2.2.1.1.5 Set of standard abbreviations	

Table 3. Human Factors, Operations, Accuracy Requirements/Issues

GPS Class C			GPS/WAAS Class Beta		RNP RNAV
Required of sensor by TSO-C129 A and/or RTCA DO-208 Shaded = exempt by TSO * = changed by TSO	Required (implied) of integrated navigation system by RTCA DO-208 (installed equipment performance)	Requirement of integrated navigation system by AC 20-130A	Required of sensor by RTCA DO 229 (including installed equipment requirements)	Required (implied) of integrated navigation system by RTCA DO 229 (Class Gamma equivalent)	Required by RTCA 192-96 for operation in RNP RNAV airspace (there may be some differences in requirements depending on the level of RNP RNAV airspace desired)
User Interface Functional Characteristics					
		9c(1)(iv)(D) Steering response		3.3.1.3.2.3 Steering response	
2.1.2 General performance		9c(1)(iv)(B) Function of connected equipment		3.3.2.3.2.1 Equipment operation	
2.1.10 Maneuver anticipation*	3.2.1.3 Lateral maneuver anticipation			2.2.1.3.10 Waypoint sequencing 3.3.2.3.2.4 Lateral maneuver anticipation	3.5.5.1 Flight progress
	3.2.1.6 Vertical maneuver anticipation			F.2.3.2 Vertical maneuver anticipation	
	3.2.1.7 Automatic altitude change (notification)			F.2.3.3. Automatic altitude change	
	3.2.1.4 Automatic lateral change (annunciation of impending waypoint crossing)			3.3.2.3.2.5/ 3.3.3.3.2.4 Automatic lateral change	
		9c(1)(iv)(L) Continuity of data during maneuver		3.3.1.3.2.7/ 3.3.4.3.2.3 Continuity of navigation data	
2.1.11 Update rate (display)*			2.1.2.6.1/ 2.1.4.6.1 Position output update rate	2.2.2.4.4 Displayed data update rate	
2.2.1.8 Position display*			2.1.2.6/ 2.1.4.6 Position output	2.2.1.4./2.2.2.4/2.2.3.4/2.2.4.4/ Navigation displays	3.5.5.2 Navigation data
				2.2.1.1.3.6 Default navigation display page	
				2.2.1.4.1/2.2.3.4.1/ 2.2.4.4.1 Primary navigation display	
2.3.1.2 Vertical path deviation	3.2.1.2 Vertical path deviation display			2.2.4.4.5 Non-numeric vertical path deviation display 3.3.4.2.2 Vertical path deviation display	

Table 3. Human Factors, Operations, Accuracy Requirements/Issues

GPS Class C			GPS/WAAS Class Beta		RNP RNAV
Required of sensor by TSO-C129 A and/or RTCA DO-208 Shaded = exempt by TSO * = changed by TSO	Required (implied) of integrated navigation system by RTCA DO-208 (installed equipment performance)	Requirement of integrated navigation system by AC 20-130A	Required of sensor by RTCA DO 229 (including installed equipment requirements)	Required (implied) of integrated navigation system by RTCA DO 229 (Class Gamma equivalent)	Required by RTCA 192-96 for operation in RNP RNAV airspace (there may be some differences in requirements depending on the level of RNP RNAV airspace desired)
2.3.1.3 Vertical profile				F.2.3.1 Vertical profile	
2.2.1.1.1 Numeric display information	3.2.1.1 Cross-track deviation display			2.2.2.4.3 /2.2.3.4.3/2.2.3.4.3 Numeric cross track deviation	3.5.5.1 Flight progress
2.2.1.1.2 Non-numeric display information	3.2.1.1 Cross-track deviation display			3.3.1.2.1 Cross track deviation display 2.2.1.4.2 /2.2.2.4/ 2.2.3.4.2 Non-numeric display/output characteristics, Non-numeric cross-track deviation 2.2.4.4.5 Non-numeric vertical deviation	3.5.5.1 Flight progress
2.2.1.2 Waypoint distance display*				2.2.1.4/2.2.3.4/2.2.4.4 Navigation Display Active waypoint distance display Active waypoint bearig display Desired track displays Waypoint distance/bearing display Horizontal protection level Missed approach waypoint bearing display 3.3.1.3.2.4 Displayed GPS/WAAS navigation parameters	3.5.5.1 Flight progresss 3.5.5.2 Navigation data 3.4.2 Displays and controls
2.2.1.3 TO-FROM indication*				2.2.1.4.6 Display of TO or FROM operation	
				2.2.1.1.3.5 Moving map	3.8 Enhanced navigation display interface

Table 3. Human Factors, Operations, Accuracy Requirements/Issues

GPS Class C			GPS/WAAS Class Beta		RNP RNAV
Required of sensor by TSO-C129 A and/or RTCA DO-208 Shaded = exempt by TSO * = changed by TSO	Required (implied) of integrated navigation system by RTCA DO-208 (installed equipment performance)	Requirement of integrated navigation system by AC 20-130A	Required of sensor by RTCA DO 229 (including installed equipment requirements)	Required (implied) of integrated navigation system by RTCA DO 229 (Class Gamma equivalent)	Required by RTCA 192-96 for operation in RNP RNAV airspace (there may be some differences in requirements depending on the level of RNP RNAV airspace desired)
2.2.1.4 Flight path selection*				2.2.1.2/2.2.3.2 / 2.2.4.2 Path selection Flight plan selection Flight plan activation Approach selection Missed approach sequencing TO-TO/TO-FROM To operation From operation	3.5.1.1. General flight planning
(a)(3)(xxii) Flight plan capability				2.2.1.2.2 Flight plan review	3.5.2.1.1 General flight planning
2.2.1.5 Waypoint entry 2.2.1.9 Input data observation* (Flight plan)	3.2.1.8 Display of selected waypoint			3.3.2.2.2 Waypoint input and display	3.5.2.1.1 General flight planning
2.2.1.6 Waypoint storage*				2.2.1.2.5 User-defined waypoints	3.5.2.1.2 User-defined fixes
2.3.1.1 Waypoint altitude				F.2.2 Flight plan - waypoint altitude	
				2.2.2.6.1/2.2.3.6.1/2.2.4.6.1 Caution associated with loss of integrity monitoring	3.5.2.1.3 Selection of RNP RNAV type

Table 3. Human Factors, Operations, Accuracy Requirements/Issues

GPS Class C			GPS/WAAS Class Beta		RNP RNAV
Required of sensor by TSO-C129 A and/or RTCA DO-208 Shaded = exempt by TSO * = changed by TSO	Required (implied) of integrated navigation system by RTCA DO-208 (installed equipment performance)	Requirement of integrated navigation system by AC 20-130A	Required of sensor by RTCA DO 229 (including installed equipment requirements)	Required (implied) of integrated navigation system by RTCA DO 229 (Class Gamma equivalent)	Required by RTCA 192-96 for operation in RNP RNAV airspace (there may be some differences in requirements depending on the level of RNP RNAV airspace desired)
2.2.1.7 Waypoint or leg sequencing*				2.2.1.3.10 Waypoint sequencing 2.2.1.3.11 TO-TO/TO-FROM	3.5.2.1.4 Fix sequencing
	3.2.1.5 Direct-to function			2.2.1.3.4 Direct-to 3.3.2.3.2.6 Direct-to function	3.5.2.2.1 Direct-to
				2.2.1.3/2.2.3.3/2.2.4.3 Path definition Fixed waypoint to a fixed waypoint Constant radius to a fix Course to a fix waypoint From leg Approach path definition Missed approach path definition Departure path definition	3.5.2.2.2 User-defined Course-to-a-fix
				2.2.1.3.7 Fly-by turns 2.2.1.3.8 Fly over turns 2.2.1.3.9 Fixed radius turns 2.2.1.3.11 TO-TO/TO-FROM 3.3.1.3.2.8 Fly-by turn performance	3.5.4 Path steering
				2.2.1.3.12 Holding patterns/ procedure turns	3.5.2.2.3 Holding
					3.5.2.2.4 Parallel offsets
					3.5.3 Navigation aid selection
		9c(1)(iv)(A) Operating modes		2.2.2.7/2.2.3.7/2.2.4.7 Mode switching requirements	3.5.5.3 Navigation modes and performance
		9c(1)(iv)(N) Operation during approaches			
				3.3.3.3.2.5 Missed approach	
		9b(9) Navigation database		2.2.1.5 Database requirements	3.6 Navigation database requirements

Table 3. Human Factors, Operations, Accuracy Requirements/Issues

GPS Class C			GPS/WAAS Class Beta		RNP RNAV
Required of sensor by TSO-C129 A and/or RTCA DO-208 Shaded = exempt by TSO * = changed by TSO	Required (implied) of integrated navigation system by RTCA DO-208 (installed equipment performance)	Requirement of integrated navigation system by AC 20-130A	Required of sensor by RTCA DO 229 (including installed equipment requirements)	Required (implied) of integrated navigation system by RTCA DO 229 (Class Gamma equivalent)	Required by RTCA 192-96 for operation in RNP RNAV airspace (there may be some differences in requirements depending on the level of RNP RNAV airspace desired)
System Integrity, Annunciations, and Alerts					
2.2.1.10 Failure/status indications*				3.3.1.3.2.2 Failure modes/annunciations	
2.2.1.13.1 General integrity requirements* 2.2.1.13.2 Annunciation of integrity alarm* 2.2.1.13.3 RAIM implementation*			2.1.1.13 Alerts/outputs 2.1.4.10 Alerts/outputs/ inputs Protection level Navigation alert Precision approach mode	2.2.1.6/2.2.2.6 / 2.2.3.6 / 2.2.4.6 Alerts Caution associated with loss of integrity monitoring Caution associated with loss of navigation Mode switching requirements	3.5.6 Alerting
		9c(1)(i)(D) Analysis of failure modes and annunciations		2.2.1.1.4 Annunciations Annunciators Messages	
			2.1.1.5 Satellite integrity status 2.1.2.2.2/2.1.4.2.2 Integrity monitoring 2.1.2.2.2.1 WAAS-provided integrity monitoring 2.1.2.2.2.2 FDE provided integrity monitoring		2.2 Containment integrity 2.3 Containment continuity
				2.2.1.4.8 Horizontal protection level	3.5.5.3 Navigation modes and performance (estimate of position uncertainty)

Table 4. Summary of Requirements

	GPS		GPS/ WAAS	RNP
	TSO-C129 & RTCA DO-208	AC 20-130A	RTCA DO-229	RTCA 192-96
Traditional Human Factors Requirements				
Controls	√	√	√	√
Operations	√	√	√	√
Accessibility	√	√	√	√
Arrangement			√	√
Labels/Readability	√	√	√	√
Inadvertent turnoff	√	√	√	√
Control/display capability	√		√	√
Displays	√	√	√	√
Visibility/Location	√	√	√	√
Brightness, contrast, and color			√	
Alphanumerics			√	
Data entry capability			√	
Equipment operating procedures			√	
Crew workload		√	√	√
Standard abbreviations			√	
User Interface Functional Characteristics				
Steering response		√	√	
Equipment operation/performance	√	√	√	
Maneuver anticipation	√		√	√
Lateral	√		√	√
Vertical	√		√	
Altitude change notification	√		√	
Lateral change notification	√		√	
Continuity of data during maneuver		√	√	
Data update rate	√		√	
Position display/output	√		√	√
Displayed GPS/WAAS navigation parameters			√	√
Default navigation display page			√	
Primary navigation display			√	
Horizontal deviation display			√	√
Vertical path deviation display	√		√	
Vertical profile	√		√	
Numeric cross-track deviation	√		√	√
Non-numeric cross-track deviation	√		√	√
Navigation display/flight progress/nav data	√		√	√

Table 4. Summary of Requirements

	GPS		GPS/ WAAS	RNP
	TSO-C129 & RTCA DO-208	AC 20-130A	RTCA DO-229	RTCA 192-96
(Active) waypoint distance display	√		√	√
Active waypoint bearing display			√	√
Desired track			√	√
Waypoint distance/bearing display			√	√
Horizontal protection level/Estimate of position uncertainty			√	√
Missed approach waypoint distance/bearing display			√	
TO-FROM indication	√		√	
Moving map/Enhanced guidance display			√	√
Flight plan/path selection	√		√	√
Flight plan activation			√	
Approach selection			√	
Missed approach sequencing			√	
TO-TO/TO-FROM			√	
TO operation			√	
FROM operation			√	
Flight plan review	√		√	√
Waypoint entry and display	√		√	
User-defined waypoints	√		√	√
Waypoint altitude	√			
Selection of RNP RNAV type/Selection of HPL			√	√
Waypoint, fix, or leg sequencing	√		√	√
Direct-to operation	√		√	√
Other path definition functions			√	√
Fixed waypoint to a fixed waypoint			√	
Constant radius to a fix			√	
Course to a fix waypoint			√	√
FROM leg			√	
Approach path definition			√	
Missed approach path definition			√	
Departure path definition			√	
Turns/path steering			√	√
Fly-by turns			√	
Fly over turns			√	√
Fixed radius turns			√	
TO-TO/TO-FROM			√	
Holding patterns procedure turns			√	√
Parallel offsets				√

Table 4. Summary of Requirements

	GPS		**GPS/ WAAS**	**RNP**
	TSO-C129 & RTCA DO-208	**AC 20-130A**	**RTCA DO-229**	**RTCA 192-96**
Navigation aid selection				√
Operating modes and switching		√	√	√
Approach operation		√		
Missed approach			√	
Database requirements		√	√	√
System Integrity, Annunciations, Alerts, and Accuracy				
Failure/status annunciations	√		√	√
Integrity requirements and alerts	√		√	√
Loss of navigation, navigation alert	√		√	√
RAIM Implementation	√			
Protection level			√	
Loss of integrity monitoring	√		√	
Precision approach mode			√	
Mode switching requirements			√	
Human factors of annunciations, messages		√	√	
Satellite integrity status			√	
Integrity monitoring			√	
WAAS integrity monitoring			√	
FDE integrity monitoring			√	
Horizontal protection level/Estimate of position uncertainty			√	√

7.2 Differences in Approval Requirements Between GPS and GPS/WAAS

A review of the comparison tables presented above shows that there are a number of similar guidelines in the GPS and GPS/WAAS requirements. There are, however, a few holes in the tables that indicate areas of differences between the requirements for the two systems. In addition, close inspection of the requirements reveals some differences.

7.2.1 <u>Traditional Human Factors Issues</u>

The first section of tables 3 (page 21) and 4 (page 27) present the requirements for traditional human factors issues. A number of the requirements are similar across the documents. While the wording and organization may be different, the intent of the requirements are mostly the same. It can be seen from the table that RTCA DO-229 provides a few more specific human factors guidelines on traditional human factors issues such as controls, displays, and workload than are provided by the other documents. This can also be seen in comparing the information provided for each guideline from the documents. For example:

RTCA DO 208
2.1.4 <u>Operation of Controls</u>
Controls intended for use during flight shall be designed to minimize errors and, when operated in all possible combinations and sequences, shall result in a condition whose presence or continuation would not be detrimental to the continued performance of the equipment. ***Controls shall be designed to maximize operational suitability and minimize pilot workload. Reliance on pilot memory for operational procedures shall be minimized (added by TSO-C129).***

AC 20-130A
9b(8) <u>System Controls</u>
All displays, controls, and annunciators must be readily readable under all normal cockpit conditions and expected ambient light conditions (total darkness to bright reflected sunlight). Night lighting provisions must be compatible with other cockpit lighting. All displays and controls must be arranged to facilitate equipment usage. Controls that are normally adjusted in flight shall be readily accessible and properly labeled as to their function. System controls and displays shall be designed to maximize operational suitability and minimize pilot workload. System controls shall be arranged to provide adequate protection against inadvertent system turnoff. Reliance on pilot memory for operational procedures shall be minimized.

RTCA DO 229
2.2.1.1.1.1 <u>Operation</u>
Controls that are normally adjusted in flight shall be accessible without interfering with the visibility of critical displays. Controls shall provide clear tactile or visual feedback when operated. The controls shall be movable without excessive effort, and detents shall be well defined. Spacing and physical size of the controls shall be sufficient to avoid inadvertent activation. Controls shall be operable with the use of only one hand.

3.3.1.1.3 <u>Operation of Controls</u>
Controls intended for use during flight shall be designed to minimize errors and, when operated in all possible combinations and sequences, shall result in a condition whose presence or continuation would not be detrimental to the continued performance of the equipment. Controls shall be designed to maximize operational suitability and minimize pilot workload. The amount of force required to activate knobs/buttons shall be acceptable, feedback to the pilot should be adequate, and risk of inadvertent activation or deactivation should be minimized. Knob shape and size should not interfere with equipment use and should help distinguish controls. Reliance on pilot memory for operational procedures shall be minimized. The control/display shall be operable with the use of only one hand. A quick-reference card summarizing the user interface to the GPS/WAAS equipment should be provided. Examples of the information expected to be included on such a reference card can be found in Section 4 of this document.

This difference (more complete and specific guidelines in RTCA DO 229) does not appear to be specifically related to the implementation of WAAS. That is, the traditional human factors information provided in RTCA DO-229 should be applicable to any GPS sensor installation.

Another observation that can be made from reviewing the above example is that there is a great deal of redundancy in the requirements both between and within the documents. Redundancy within a document probably could be lessened through document organization. Redundancy is to be expected between documents and would not be a problem if all of the documents stated the same thing. However, since there are minor differences, individuals evaluating systems may have to read several documents to make sure that all issues are covered. It does appear that the requirements provided in RTCA DO-229 include all of the requirements of the other documents (and more) so that a system that meets the human factors criteria of RTCA DO-229 should at least meet the requirements of the other documents.

One final observation on the presentation of traditional human factors items in these documents is that the information is highly subjective. The outcome of the evaluation will be dependent on the evaluator. RTCA DO-229 has made some effort to reduce the subjective nature of the task by providing procedures and checklists for human factors bench tests. These checklists are based on the FAA Human Factors and Operations Checklist for Standalone GPS Receivers previously discussed. RTCA DO-229 has also provided a few quantitative measures such as minimum character size and recommended minimum times and numbers of actions for various equipment functions are provided by RTCA DO-229. Minimum button or knob size and separation is not included. It is understandable that there is resistance to providing information that may limit future development of better products, however, the information may be presented in a way that indicates that it is reference information for the evaluator and not necessarily a requirement.

7.2.2 <u>User Interface Functional Characteristics.</u>

The second section of the tables (pages 22 to 26 for table 3 and page 27 to 29 for table 4) presents user interface functional characteristics. These requirements specify system operation, display characteristics, and pilot controllable functions. In comparing the requirements of the documents, it is clear that RTCA DO-229 for GPS/WAAS has more detailed requirements for the functional characteristics of the equipment and the user interface than does RTCA DO-208 for GPS. Some of the differences between the sets of documents include:

1. RTCA DO-229 lists specifically what data must be displayed continuously and what data must be displayed continuously or on a default navigation page that can be accessed with a single action in two seconds or less.
2. RTCA DO-229 requires that equipment have both TO-TO and TO-FROM operational capability while RTCA DO-208 and TSO-C129 do not have this requirement.
3. RTCA DO-229 also specifies the presentation of the following data that is not specifically required by RTCA DO-208 and TSO-C129 including:
   a) Active waypoint bearing display
   b) Desired track
   c) Horizontal protection level
   d) Missed approach waypoint distance display
   e) Missed approach waypoint bearing display
   f) Non-numeric vertical deviation
4. RTCA DO-229 specifies in greater detail the functionality and interface required for flight path definition and selection.

5. Some of the quantitative requirements in terms of display resolution, accuracy, linearity, and deflection requirements are slightly different between the two documents.
6. TSO-C129 does not require approach mode selection and sequencing for Class C equipment, though it is expected that this is an error in the document since TSO-C129 does describe an addition of approach mode selection and sequencing to the RTCA requirements for Class A equipment (section (a)(3)(xii)).

The presentation of horizontal protection level with GPS/WAAS is due to the new concepts of integrity and accuracy that are being implemented with GPS/WAAS equipment (described in more detail in the following section). A few of the other differences are due to the expected (though it is not allowed in the current draft of TSO-WAAS) use of GPS/WAAS for precision approach, whereas GPS may only be approved for nonprecision approach. Most of the differences between the interface functional requirements for GPS versus GPS/WAAS do not appear to be due to fundamental differences between the GPS and GPS/WAAS equipment. Many of the differences may simply be due to the natural progression of knowledge of the systems between the time of production of the GPS information and the GPS/WAAS information. In general, equipment that meets the Minimum Operational Performance Standards of GPS/WAAS equipment should more than meet the requirements of GPS equipment.

Manufacturers of GPS/WAAS equipment may be interested in manufacturing equipment that will meet the requirements of both TSO-C129 and TSO-WAAS since the full implementation of the WAAS network may not be complete for some time. Users could then use GPS only when WAAS systems were unavailable and use GPS/WAAS when WAAS was available. The intent of the WAAS MOPS was to create requirements to replace TSO-C129 so that systems that meet the requirements of the WAAS TSO can be used to fly both GPS and GPS/WAAS operations so that manufacturers need to reference only the WAAS MOPS for both types of operations (DeCleene, 1996).

7.2.3 System Integrity, Annunciations, and Alerts

The final section of table 3 (page 26) and table 4 (page 29) covers system integrity, annunciations, alerts, and accuracy. This is one area where differences between the two system approval requirements are expected since GPS/WAAS provides a completely different method of ensuring navigation integrity than is provided by GPS alone. Annunciations and alert requirements associated with integrity monitoring and navigation failure are slightly different. GPS/WAAS equipment is expected provide better accuracy and better integrity monitoring and, therefore, is expected to be approvable as providing the "primary means" of navigation. Because of this, more stringent requirements on accuracy and integrity are imposed on GPS/WAAS equipment.

The requirements from the documents indicate that there are differences between GPS and GPS/WAAS in these areas. The techniques used to measure accuracy and integrity are different for GPS and GPS/WAAS. The GPS/WAAS approval documentation introduces a new measure of accuracy called pseudorange error (versus position fixing error for GPS). The concept of horizontal and vertical protection levels also are introduced and must be used in integrity checking for GPS/WAAS.

The requirements for Class C sensors list the form that alerts and annunciators must take by requiring equivalence to Class A equipment. The requirements do not list the form of the information (or output of the sensor) to be passed to the equipment providing the alerts. The requirements in RTCA DO-229 list specifically the information that Class Beta sensors must output to be used in alerts. RTCA DO-229 specifies the form of the alerts and annunciators of Class Beta sensors through the requirement that installed Class Beta sensors have performance equivalent to Class Gamma and Delta equipment.

There are other differences in the requirements of GPS versus GPS/WAAS equipment than the means of measuring accuracy and integrity. These differences are in the form of the presentation of alerts. The main difference between the alert presentation requirements for GPS versus GPS/WAAS equipment is that the GPS approval requires alerts on the primary navigation display in more situations than are required for GPS/WAAS approval. Also the GPS requirements state removal or flagging of potentially incorrect navigation data on the display. The GPS/WAAS requirements recommend, however, that the navigation data continue to be displayed in these situations. Finally, there appear to be differences in the requirements for annunciations at the time of mode switching (changes to the display or system that occur in conjunction with changes in phase of flight).

Additionally, there are differences between the requirements for GPS and GPS/WAAS dealing with system integrity, annunciations, and alerts. As discussed above, it is the intention of the WAAS MOPS to replace the GPS requirements so that systems that meet the WAAS requirements may also be used for GPS operations when the WAAS is not operational.

The human factors aspects of the annunciator design should be similar for GPS and GPS/WAAS, though RTCA DO-229 is the only document that provides a complete description of what factors to evaluate to ensure good human factors design of annunciators.

7.3 Impact of RNP on the Approval of GPS and GPS/WAAS Sensors

Many of the same approval requirements for GPS and GPS/WAAS equipment are listed in the RNP RNAV MASPS. Table 4 shows that the RNP MASPS requirements are slightly more detailed than the GPS requirements and slightly less detailed than the GPS/WAAS requirements. The issues described in section 7.2.1 apply also to the traditional human factors issues associated with RNP approvals. Many of the requirements are the same though they may be worded slightly differently. There are no fundamental differences for systems to be used as RNP RNAV equipment versus GPS or GPS/WAAS equipment in terms of traditional human factors issues.

There are a few user interface functionality requirements that are unique to RNP RNAV approvals. These include 1) selection of RNP RNAV type, 2) navigation aid selection, 3) estimate of position uncertainty (and alerts associated with required RNP type) 4) parallel offsets and parallel offset status alerting, and 5) capability to fly published RNP RNAV holding procedures. The differences between the RNP requirements and the GPS and GPS/WAAS requirements are generally due to the use of the RNP concept for accuracy and integrity and due to the more general applicability of the RNP document to all RNAV equipment rather than only GPS or GPS/WAAS equipment. Of these five differences, the first three are met by equivalent means in the WAAS MOPS, including selection of HAL and display of HPL.

With the exception of the requirements for parallel offsets and the capability to fly published RNP RNAV holds as described in the RTCA 192-96, equipment that meets the human factors and operations requirements of RTCA DO-229 for GPS/WAAS should meet the requirements of RNP equipment. Equipment certified to TSO-C129 rather than TSO-WAAS will have to be evaluated more carefully to ensure that all of the additional requirements of RTCA 192-96 have been met.

8. CONCLUSIONS

Aircraft certification specialists face a daunting task in the approval of GPS and GPS/WAAS sensors in low-end transport category aircraft. The documentation available does not clearly separate sensor equipment and integrated navigation system requirements. For GPS systems, evaluation requires that specialists either modify RTCA DO-208 with the information listed in TSO-C129 or flip back and forth between the documents (and within the TSO-C129 document). The presentation of information in TSO-C129 is often difficult to interpret for the installation of sensors since the document states that the sensors are exempt from several requirements yet it also states changes to those requirements or equivalent performance requirements. There are also, potentially, a few errors in TSO-C129 (for example, omission of a portion of a table on page 27, omission of pressure/barometric altitude input information) that exacerbate the problem of interpreting the information. These types of problems also inevitably lead to misunderstandings with manufacturers.

For GPS/WAAS equipment installations, the information provided in RTCA DO-229 is more complete and there (currently) are few exceptions to the document specified in TSO-WAAS. However, there are some ambiguous requirements in this document as well, especially in the distinction between sensor equipment approval and integrated navigation equipment installation requirements. There are several sections of the document with redundant information and readers may have difficulty determining which sections actually apply to a given situation or may find themselves reading the same requirements in different places. For example, some of the Class Gamma installed equipment requirements are the same as Class Gamma general requirements, though the organization and wording may be slightly different. The same is true for the Class Gamma equipment test procedures and the installed equipment test procedures. There are a few differences between requirements of GPS and GPS/WAAS equipment that appear to be due to the recency of information for the GPS/WAAS document. For this reason, certification specialists reviewing GPS equipment may choose to supplement the GPS requirements with the more complete and more recent applicable information in the GPS/WAAS document.

Navigation equipment manufacturers interested in ensuring that GPS or GPS/WAAS equipment meets RNP RNAV standards that may be imposed for certain airways and procedures face another approval document. RTCA 192-96 is in draft form and there is currently no draft FAA document supporting the MASPS for RNP RNAV. With the exception of the requirements for parallel offsets and the capability to fly published RNP RNAV holds as described in the RTCA 192-96, many of the human factors and operations requirements in this document are the same as those for GPS/WAAS and equipment meeting GPS/WAAS requirements should also meet RNP RNAV requirements.

This review showed that there were a few problems with the documentation and process for GPS and GPS/WAAS Class C sensor approvals. Generally, the documentation is thorough, but in some cases is difficult to interpret and cross-reference. There are efforts underway to account for some of the problems discussed. First, TSO-C129 is being updated (TSO-C129B) to refer to the newer requirements of RTCA DO-229. Second, a checklist for approval of GPS/WAAS equipment is under development.

9. REFERENCES

Adler, E.L. and Ruelos, C.H. 1993. GPS - Global Positioning System, Using the Global Positioning System for Navigation on Boeing Airplanes. *Airliner.* October-December.

DeCleene, B. 1996. Personal communication.

Department of Transportation and Department of Defense 1993. *1992 Federal Radio-navigation Plan.* DOT-VNTSC-RSPA-92-2/DOD-4650.5. Washington, DC.

Federal Aviation Administration. 1992. Technical Standard Order, TSO-C129a, Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS). Washington, DC.

Federal Aviation Administration. 1994. Advisory Circular, AC 120-CNS Draft 4 Rev 1, Criteria for Approval of Required Navigation Performance (RNP) for Air Carrier Operations. Washington, DC.

Federal Aviation Administration. 1996. Advisory Circular, AC 20-130A, Airworthiness Approval of Navigation or Flight Management Systems Integrating Multiple Navigation Sensors. Washington, DC.

Huntley, M.S., J.W. Turner, C.S. Donovan, and E. Madigan. 1995. *FAA Human Factors and Operations Checklist for Standalone GPS Receivers (TSO-C129 Class A).* (Report No. DOT-VNTSC-FAA-95-12). Washington, DC: Federal Aviation Administration.

Joint DOD/DOT Task Force on GPS. 1993. *The Global Positioning System: Management and Operation of a Dual Use System.* A Report to the Secretaries of Defense and Transportation. Washington, DC: Joint DOD/DOT Task Force.

McAnulty, M.D. 1994. *A Review of Principles and Guidelines for the Design of Controls and Displays for Stand-alone GPS and LORAN Receivers.* Ft. Rucker, Alabama: Anacapa Sciences, Inc.

RTCA. 1991. RTCA/DO208, *Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS),* Washington, DC: RTCA.

RTCA, Inc. 1996. *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment.* RTCA Document No. RTCA/DO-229. Washington, DC: RTCA, Inc.

Wright, M.C. 1996. *Global Positioning System: A Guide for the Approval of GPS Receiver Installation and Operation.* (Report No. DOT-VNTSC-FAA-96-18). Washington, D.C.: Federal Aviation Administration, Satellite Operational Implementation Team.